Research and Development for the Liquid Argon Time Projection Chamber

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ABSTRACT

When cosmic rays interact with Earth's atmosphere, particles, most of which are pions, are emitted which decay into muons. These can be detected on the surface with scintillation counters attached to photomultiplier tubes. Eighteen different plastic scintillation counters will be used for this purpose for use in the Liquid Argon Purity Demonstrator (LAPD). In Phase I of the LAPD, it was shown that the required purity of the liquid argon can be obtained without first evacuating the vessel. In Phase II, this purity will be demonstrated using cosmic rays. Phase II consists of the "Long-Bo" Time Projection Chamber. The time projection chamber is 2 m tall and 30 cm in diameter. A voltage of 100 000 V is applied to cause electrons excited by the cosmic ray muons to drift up to a wire array. Scintillation counters will be placed on the outside of the tank to directly measure the muons before and after they pass through the liquid argon. When the scintillation counters were tested, it was seen that the scintillation counters have efficiency consistent with 100%, but can appear to have lower efficiencies due to air showers. The primary operating voltage was determined based on the peak of the pulse area performance. A system for mounting the scintillators was designed, fabricated, and installed. The counters are arranged in groups of three every 60° around the tank. Additionally, resistive temperature devices were tested at temperatures ranging from -160 to 70 °C, and it was seen that the resistance changes at about 0.4 ohms per degree Celsius. These will be used in the LAPD to determine and monitor temperature gradients. Finally, a model time projection chamber was fabricated with which to model insertion of the real unit. Liquid argon represents the future of neutrino experiments and the intensity frontier, and work on the LAPD will help show that this is a viable option for continuing experiments.

I. BACKGROUND

A. Cosmic rays

Cosmic rays consist primarily of protons, alpha particles, and heavy nuclei. The flux of these particles is dependent upon the solar cycles. These particles are subject to the strong interaction, and when they enter the Earth's atmosphere, they interact with the nuclei of the atoms that make up the atmosphere, namely nitrogen and oxygen. These interactions produce mostly pions as well as kaons and other mesons and hadrons. If the hadrons are sufficiently energetic, they will interact with other nitrogen and oxygen nuclei themselves which helps to build up air showers. The pions that are created decay into muons and neutrinos, we can then detect the muons on the surface. Even though the lifetime of a muon is approximately 2.2×10^{-6} seconds - which at the speed of light is only 660 meters - they do generally reach the surface due to time dilation and the fact that they do not interact by the strong force.[1]

B. Scintillation counters

These muons can be detected with scintillation counters. Plastic and other organic scintillators work via the Stokes shift. The Stokes shift is the difference between the energy required to excite a valence electron and the energy of the photon produced when the electron de-excites. In a material with no Stokes shift, any photon released in a de-excitation will be absorbed by a neighboring molecule. [3] Plastic scintillation counters have a highly polished surface that reflects the photons produced at angles down to the critical angle of the material so that they travel along the length of the counter with minimal loss of light. The scinitllators that were used in this experiment shifted outgoing light to blue which then was guided into a photomultiplier tube.

In the photomultiplier tube, the incident photon from the scintillator hits a photocathode, and produces an electron via the photoelectric effect. This electron then goes on to hit a dynode and engage in stimulated emission so that two (or more) electrons come off the dynode, both of which hit the next dynode, and so forth until the end of the tube where there is an anode and the accumulated electrons are read out as a current. The phototube is powered by a high voltage so that each successive dynode has a higher voltage, thus inducing the electric field which causes the electrons to flow towards the dynode. [2]

C. Liquid Argon Purity Demonstrator (LAPD)

The Liquid Argon Purity Demonstrator (LAPD) is a tank that is 3 meters in diameter and 3 meters tall. It can hold 30 tons of liquid argon.

In phase one of the Liquid Argon Purity Demonstrator, the goal was to show that Liquid Argon could attain sufficient purity, as measured by electron drift times, in such a large vessel without evacuating the tank first. Paths can only be measured if the argon in the tank is free of non-noble elements, which would absorb the electrons that were being measured. In previous liquid argon detectors, a vacuum is created then the liquid argon is inserted. In such a large volume, however, this is not feasible. Instead, argon gas was used as a piston to push the air out of the tank then the tank was filled with the liquid argon. Additionally, filters were added to remove both water and oxygen. Water was removed by way of a molecular sieve, and oxygen by a Trigon filter which is made of copper and reacts with the oxygen. The Trigon filters are depleted over time and must be regenerated by reversing the oxidation reaction. The electron drift-lifetime was measured with devices called Purity Monitors. These devices are from 20 cm to 50 cm long and use a very low electric field to simulate a longer drift (meters) at a higher electric field.

In Phase II, the LAPD will have Long-Bo, a Time projection chamber (TPC) installed in it and scintillation counters on the outside in order to measure cosmic rays. The base of the TPC will be held at -100,000 V, while the top is held at ground, inducing an electric field pointing down. When the cosmic rays hit the liquid argon, their energy will ionize the argon, and the electric field will send the electrons upwards and the Ar+ ions down. At the top of Long Bo, the electrons will then hit three different planes of wires which will uniquely determine the path that the cosmic ray took. The scintillation counters serve as a trigger to the electronics of Long Bo so that once a cosmic ray hits one counter, the signals from the electronics for measuring the path are recorded. [2]

II. RESULTS AND ANALYSIS

A. Scintillation counters

The counters we were using are 1.5 meters long, 15 centimeters wide, and 2 cm thick. The outputs of the counters were measured with NIM coincidences and scalers.

We began by testing each counter for light leaks. A light leak occurs when the covering on the scinitillator is no longer effectively blocking light from entering the plastic. This causes photons that are not a result of cosmic rays to enter the photomultiplier tube (Seem Fig. 1). If these are not eliminated, then the rest of the project would be ineffective.

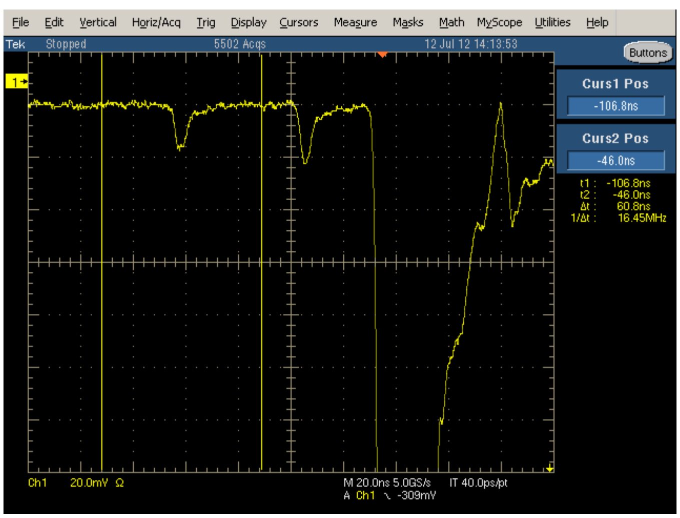

Fig. 1. The large pulse on the right is due to the cosmic ray, the smaller pulses to the left are due to light leaks.

Next, we determined travel time for a signal to go from one end of a counter to the other. We placed a small (10 centimeter) counter on the far end of a regular counter and noted the difference in times between the signals being recorded. Then we moved the small counter to the other end of the counter and noted this time difference. The difference of these two differences was found, which is the amount of time the signal took to go from one end to the other of the counter. On average this time was 10 ns. Using this information we were able to determine the index of refraction for the counters. The following calculation was performed in which θ_c indicates the critical angle, n is the index of refraction, v is the speed of light in the medium, c is the speed of light in a vacuum, d is the length of the counter, and s is the distance traveled by the light.

$$\sin \theta_c = 1/n$$

$$v = c/n$$

$$1/\sin(\theta_c)*d = s$$

$$s/t = v$$

$$1/(t*\sin(\text{arctsin}(1/n))*d=c/n$$

$$1/(10x10^{-9}(\sin(\arcsin(1/n))) *1.5= 3x10^{8}/n$$

$$n=3(\sin(\arcsin(1/n)))/1.5$$

n must be positive and real, so $n = 1.41$

Efficiency of the counters was then tested in two different ways. The first way was to arrange the counters standing upright or horizontally separated by a distance with two counters between them. In doing this, we were able to test the efficiency of the counters in the center. As, if the three counters other than the counter being measured counted a cosmic ray, but the one did not, this would indicate inefficiency in that counter. Table 1 displays the results from this test. Uncertainty was determined using the classical root-n-p-q method where q is equal to 1-p.

Distance	Efficiency	Counter Removed	Uncertainty	Counter Position
2	8.19E-01	21	2.28E-03	Vertical
2	8.41E-01	138	2.19E-03	Vertical
2	8.13E-01	47	1.86E-02	Vertical
2	8.42E-01	138	1.77E-02	Vertical
0.5	9.80E-01	47	1.11E-03	Horizontal
0.5	9.74E-01	138	1.24E-03	Horizontal
0.5	9.87E-01	21	9.14E-04	Horizontal
0.5	9.88E-01	138	8.50E-04	Horizontal
1	9.62E-01	21	5.33E-04	Horizontal

1	9.67E-01	138	4.08E-03	Horizontal
0.5	9.79E-01	21	3.73E-03	Vertical
0.5	9.74E-01	138	4.24E-03	Vertical
1	9.30E-01	21	5.69E-03	Vertical
1	9.27E-01	138	5.80E-03	Vertical

Table 1.

Efficiency of individual counters was also tested by placing the counter being tested horizontally between two other counters. We counted the number of coincidences between the top and bottom counter compared to the number of coincidences between all three counters. We repeated this test through the full range of voltages. We found plateau curves for each individual counter. Best efficiencies and recommended operating voltages for each counter are displayed in Table 2. Voltage was limited to 1700 volts because above that the photomultiplier tubes experienced degradation and nearby counters would detect electrons from these tubes. Counters that had efficiencies below 91% were not used.

Counter #	Recommended Voltage (V)	Max Efficiency (%)
98	1600-1680	91.9
138	1640-1700	98.6
18-44	1500-1700	98.6
132	1580-1700	98.6
145	1660-1700	98.5
6	1580-1700	98.2
131	1600-1700	98.2
101	1500-1700	98.3
16	1560-1680	96.8
21	1560-1681	97.3
2	1520-1680	97.7
11	1520-1681	97.8
95	1700+	91.2
19-77	1680-1700	96.2
115	1720+	91.2
80	1480-1680	97.1
4	1480-1680	97.8
47	1400-1700	97.6

149	1440-1700	92.7
41	1700	96.7
10	1660-1700	92.4
91	1700	75.3
18	1640-1799	94.2
35	1520-1700	94
1	1480-1700	92.6

Table 2

When the counters were vertical, the efficiency seemed to trend inversely with the separation distance. Though, in the horizontal tests, the separation did not cause a significant change in the efficiencies. This discrepancy is explained by air showers. When the cosmic rays interact in the upper atmosphere, many secondary particles are created, which can reach the ground at the same time. The first efficiency test that we did assumes a predominantly horizontal angle being taken by the muons, but the second test measures a predominantly vertical distribution. In the first test, the apparent low efficiencies were not due to the counters, rather due to the fact that there was no ray going through the measured counter, even though there was one going through the ones to the outside.

B. Scintillator holders

The scintillators needed to be held as close as possible to the tank while remaining vertical. It was planned that there would be six places spaced evenly around the tank, and in each space there would be three different counters to maximize the coverage over the full length of the Long-Bo TPC.

We determined the correct location for each of these groupings based on the pre-existing infrastructure surrounding the tank. We then designed and installed the scintillator holders. The scintillators were positioned on ladders. The two bottom counters are positioned in such a way that the flat edge is cradled by the aluminum stand and the top edge is prevented from falling via another piece of aluminum. In the case of each of these holders, the backing is long enough to hit the rung below the one that it is hanging from, in order to prevent the holders from swinging backwards. See Figure 2. The top counter on each ladder is hung with the phototube pointing downwards. The bracket on this end is angled to follow the light guide. Electrical tape is used to prevent the counter coming out the front. The same holder as before is used to prevent the scintillator tipping forward at the top end.

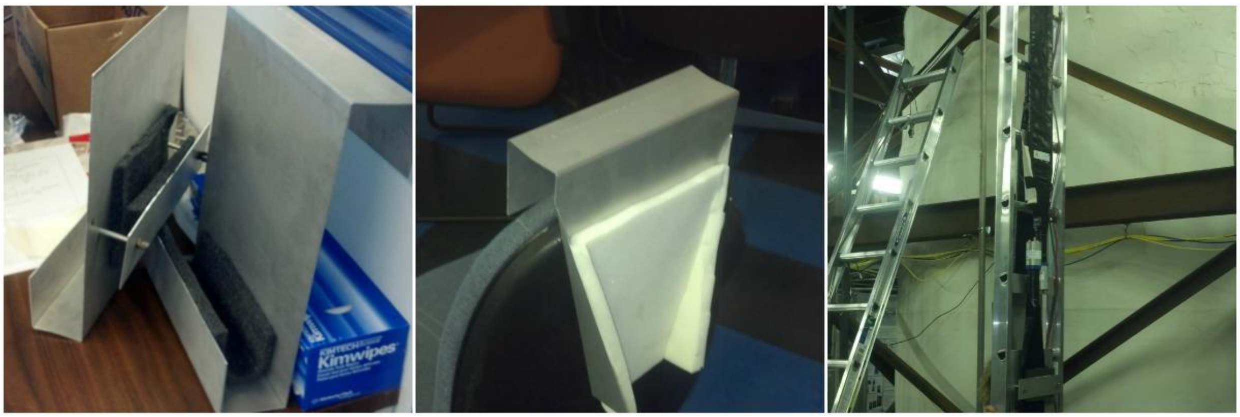

Figure 2. Left: Top and bottom holders for the bottom two counters. Center: Bottom holder for the top counter. Right: All three counters mounted on a ladder.

C. Resistive Temperature Devices

Resistive Temperature Devices (RTDs) will be used in the LAPD to measure the temperature gradient both while it is being filled and during operation.

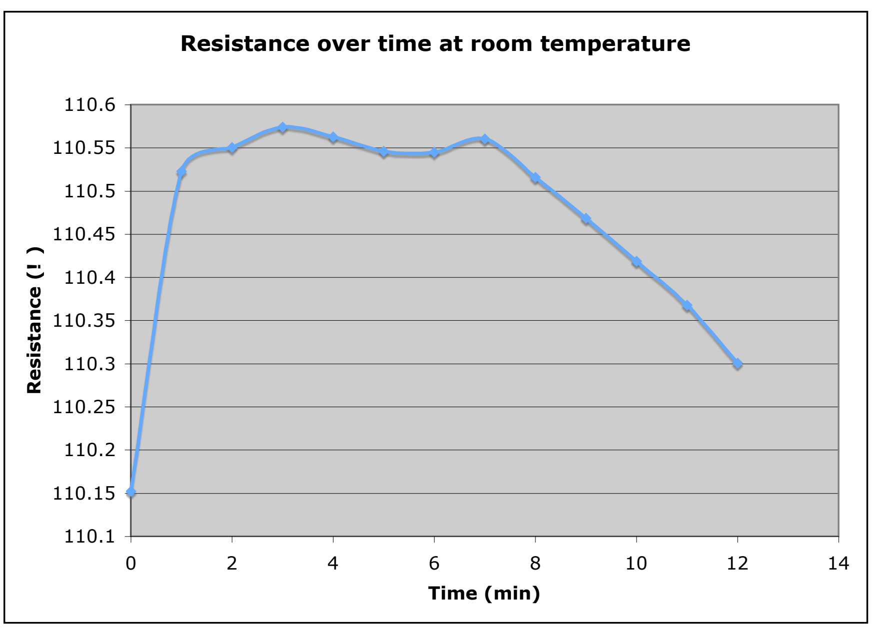

Figure 3.

We first tested the RTDs at room temperature over time. (See Figure 3) We determined that the best time to measure the temperature from these devices was between 1 and 8 minutes, otherwise the readings were inconsistent, most likely due to power output of the resistors.

We then determined what the actual temperature readings should be seen as based on the resistance reading. The RTDs were heated in an oven to obtain high-temperature measurements, and submerged in liquid nitrogen to find the low-temperature measurements. This was done with each of the three RTDs that will be used in the LAPD. We found that the RTD resistance did vary linearly with temperature at a rate of $0.4\ \Omega/^{\circ}\mathrm{C}$ See Figure 4.

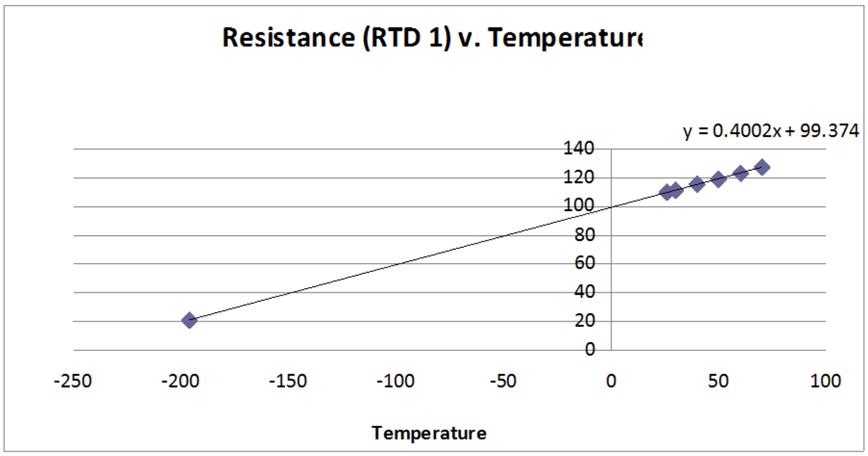

Figure 4

D. Model time projection chamber

The “Long-Bo” Time Projection Chamber (TPC) is two meters high and contains fragile electronics. Inside of PC4 where the LAPD is located, the ceiling is very close to the top of the tank. Insertion of the TPC must be practiced before it is done with the real one. Thus, we created a 1:1 scale model with which to practice this insertion.

This model TPC was made primarily out of concrete forming tubes with foam blocks representing the electronics that are at the top of the real chamber. The method for threading the cables was also determined in making this model. Pictured in Figure 5 is both the model TPC and the actual one for comparison.

Figure 5. On the right is the actual "Long-Bo" Time Projection Chamber, and on the left is the model TPC.

III. CONCLUSIONS AND FUTURE WORK

The experimental portion of LAPD Phase II will commence in mid to late August. This will serve to demonstrate the viability of this type of system for use in other experiments, mostly involving neutrinos. The 35-ton membrane cryostat that is being built will use the same purification system as the LAPD and begin the use of this technology for a Long-Baseline Neutrino Experiment. In such an experiment, a neutrino would interact with a proton or neutron which would create particles that can ionize the liquid Argon. (Figure 6) And thus be detected in a similar way to how the cosmic ray muons are will be detected in the LAPD.

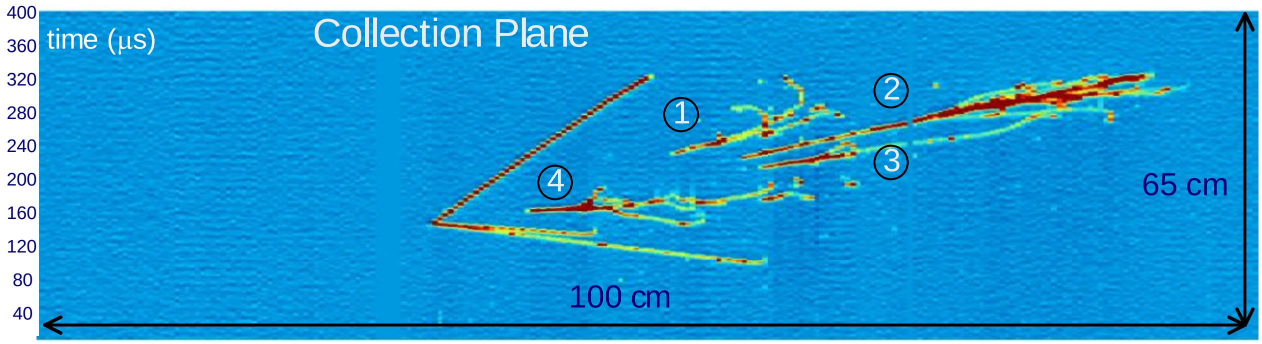

Figure 6. Tracks are those of charged particles. This even includes 4 photons which are numbered 1 through 4 in the image.

IV. ACKNOWLEDGEMENTS

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References

[1] P.K.F. Grieder, *Cosmic Rays at Earth.* New York: Elsevier Science B.V., 2001.

[2] W.R. Leo, *Techniques for Nuclear and Particle Physics: A How-To Approach.* New York: Springer-Verlang, 1992.\

[3] M. Longair, *Theoretical Concepts in Physics: An Alternative View of Theoretical Reasoning in Physics,* 2nd ed. Cambridge: Cambridge University Press, 2003.

[4] B. Pahlka and C. Johnson. *The Liquid Argon Purity Demonstrator*. Poster presented at TIPP 2011.